Multiaxial fatigue criterion accounting for anisotropy in forged components

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ABSTRACT: Numerical modelling of fatigue behavior for anisotropic structures has become critical for design applications. This is particularly true for forged components due to the intrinsic anisotropy of the material resulting from the process. The aim of this study is to relate the microstructure scale to the process scale, i.e. the engineer scale. Anisotropy induced by the forming process and the most relevant feature which results from forging, is the preferential orientation of structural defects and grains in the direction of the deformation. Grain flow is modelled using a fiber vector at the level of the representative elementary volume. It can then be used to improve and refine the Papadopoulos fatigue criterion by taking into account fatigue limits for each direction of anisotropy. In practice, it is very tedious to determine precisely these fatigue limits and impossible to obtain experimentally all of them for each direction of uniaxial loading. To circumvent this difficulty, we simulate the problem at the microstructure scale by considering fiber vector as the result of the inclusion and grain orientation. Microstructures are then precisely modelled using DIGIMICRO software. A representative elementary volume including inclusions is meshed and high cycle fatigue simulation is performed. The results can be used in order to optimize the preform of the component before simulation.

KEYWORDS: High Cycle Fatigue Multiaxial Criterion - Fiber Vector - Digital Material - Multiscale approach

1 INTRODUCTION

Among all forming processes, forging gives raise to the most resistant components withstanding a large number of loading modes. However, forging induces a strongly heterogeneous microstructure in the material. High mechanical properties of such material are directly related to this heterogeneity or anisotropy. The problem is the numerical representation of this anisotropy. In practice, high cycle fatigue simulations are performed without accounting for the past of the component and even less anisotropy. In most cases, only geometric form and residual stresses stemming from the process are used. Therefore, it is necessary to adapt traditional high cycle fatigue criteria which were developed assuming isotropy to anisotropic material behavior configurations. Thus, the ANR (French National Research Agency) Optiforge project was launched. Its goal is to account for the forming process and its effect on the microstructure to perform high-cycle fatigue studies. A virtual simulation chain is created between the forming process and the microstructure history. The Papadopoulos criterion [5] was finally chosen to develop a microstructure scale approach based on forging characteristics. A representative elementary volume is meant to describe explicitly the shape and orientation of both inclusions and grains. This microstructure study is performed using the DIGIMICRO software [1]. Figure (1) sums up the objectives of this project.

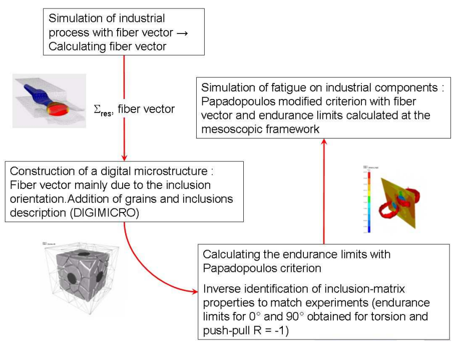

Figure 1: Objectives of the project

2 CHARACTERISTICS OF A FORGING PROCESS

Forging processes induce, inevitably, high level of deformation giving raise to anisotropy of the components. Indeed, due to the reduction of the section, the matter follows the deformation. This phenomenon is also called grain flow orientation. The extension and the orientation of the matter is directly related to the kneading rate undergone by the matter. The kneading K_n is defined by the ratio of the initial section S_0 over the final section S: K_n = S_0/S.

The fiber vector is given by the definition of the gradient tensor $\underline{\underline{F}}$ given by (1):

$$\underline{\underline{F}} = \underline{\underline{I}} + \underline{\underline{Grad}}\,\underline{X} = \underline{\underline{R}}\,\underline{\underline{U}} = \underline{\underline{V}}\,\underline{\underline{R}}, \qquad (1)$$

where $\underline{\underline{I}}$ is the unit tensor, $\underline{X}$ is the displacement vector, $\underline{\underline{R}}$ is an orthogonal orientation tensor, $\underline{\underline{V}}$ and $\underline{\underline{U}}$ are symmetric positive tensor named respectively left distortion and right distortion. This is the polar decomposition of $\underline{\underline{F}}$.

The vector is given by:

$$d\underline{X} = \underline{\underline{F}}\,d\underline{X_0}, \qquad (2)$$

where $d\underline{X}$ is the current position and $d\underline{X_0}$ is the initial position. For instance, figure (2) shows a cambering process with an initial grain flow orientation along the rod.

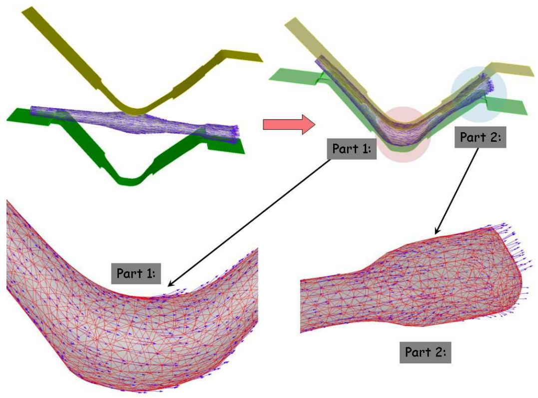

Figure 2: Flow orientation for a cambering process

3 THE CRITICAL PLANE APPROACH FOR FATIGUE CRITERIA

Standard high cycle fatigue criteria are determinist criteria, which means that for a calculated stress field and intrinsic parameters of the material, they provide a unique domain of validity. For most criteria, this domain is defined using a critical line in a specific space. This is the case of the Papadopoulos criterion [5]. The main idea consists in splitting a given structure into many sub-volumes which could be considered as representative elementary volumes (figure 3). Then, the maximum stress over a complete loading cycle is computed to determine when the structure breaks up.

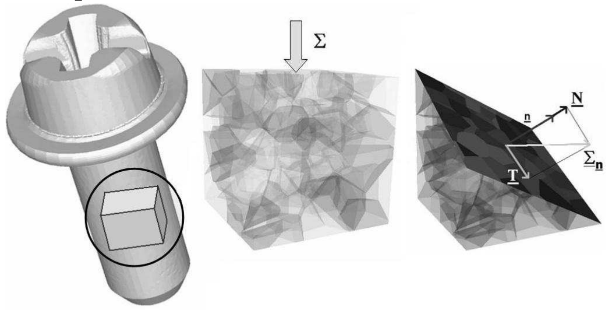

Figure 3: Schematics of a Representative Elementary Volume (R.E.V.)

To calculate this critical stress level for each R.E.V., it is assumed that an adapted state (or shakedown state) with a purely elastic behavior at the grain level, has been reached. Indeed, at the macroscopic level, the structure might be seen as undergoing an elastic loading but, locally, at the microscopic level, it may be possible that one or several grains are unfavorably oriented, thus leading to a local plastic behavior. This adapted state is reached after a few cycles (typically about 1000 cycles). Figure (4) shows the progressive stabilization at the microstructure level; Σ is the macroscopic stress, σ is the microscopic stress (for each grain), E is the macroscopic and ϵ the microscopic strain obtained from the Lin-Taylor approach. If no shakedown state can be reached, a crack is initiated at the microscopic level; it will lead to a macroscopic crack after some cycles. If $\underline{\Sigma_n}$ is the stress applied onto a cross section (plane of normal $\underline{n}$) of the representative elementary volume (figure 3), its projection onto the plane is the shear stress $\underline{T}$. The goal of these criteria is to investigate iteratively many different plane orientations in order to find the maximum value of the shear stress. Moreover, the effect of the hydrostatic stress ($\sigma_{ii}/3$) has to be added [8]. The secure domain is defined by:

$$T_\Sigma + \alpha\,\Sigma_{H,max} \leq \beta, \qquad (3)$$

which defines a linear domain as seen in figure (5). If the curve described by the shear stress projected onto the critical plane is below a line so-called threshold, there is no initiation of macroscopic crack (figure 5). Generally, T_Σ is the $max_{\underline{n}}\, max_{t\in[0,P]}$ $\underline{T}$ value on the critical plane where P is the loading period and $\Sigma_{H,max}$ is the maximum hydrostatic stress over the loading cycle [4]. Coefficients α and β are deduced from two reference fatigue limits (with a stress load ratio $R = \sigma_{min}/\sigma_{max}$ = -1) from tension $\boldsymbol{s}$ and torsion $\boldsymbol{t}$ data:

$$\alpha = \frac{\boldsymbol{t} - \frac{\boldsymbol{s}}{2}}{\frac{\boldsymbol{s}}{3}}, \quad \beta = \boldsymbol{t}. \tag{4}$$

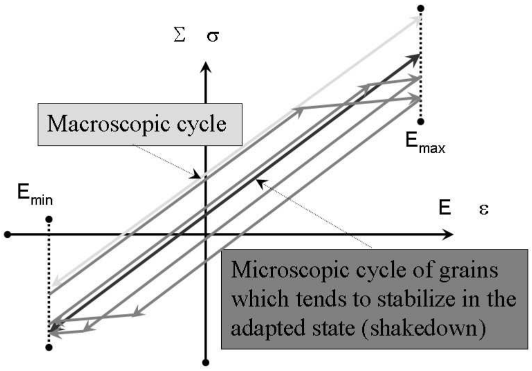

Figure 4: Macroscopic behavior of the structure and microscopic behavior of a grain misoriented which undergoes a plastic deformation

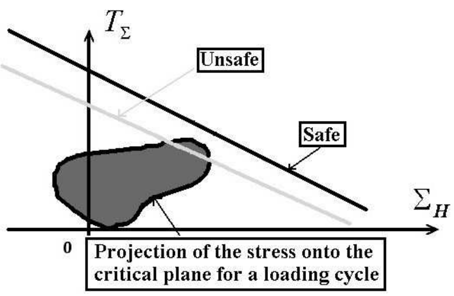

Figure 5: Threshold domain for a determinist fatigue criterion

Standard high cycle fatigue criteria predict efficiently the failure of an isotropic component (like casting component) but they are not reliable for forged components due to anisotropy.

4 THE NEED FOR A MESOSCOPIC APPROACH

The only means to perform a more trustworthy simulation is to take into account the microstructure. Indeed, most of fatigue cracks appear in the vicinity of an inclusion, especially for hard materials. In fact, the resistance to a high cycle fatigue uniaxial loading is very different for two materials composed with approximately the same constituents but with a different number of inclusions [7]. Generally, the resistance is lower for the material containing more inclusions. Moreover, the endurance limit is higher in the direction of the grain flow compared to the transverse direction. These differences are directly related to the microstructure. To bring out this results, we have been working on a bainitic steel METASCO® MC. Several analysis show that the probability of crack initiation is high near MnSs inclusions (manganese sulphide), very common in modern steels due to their benefic role during machining (figure 6) [7]. For that reason, a new pre-processor, DIGIMICRO, is used to create realistic digital microstructures.

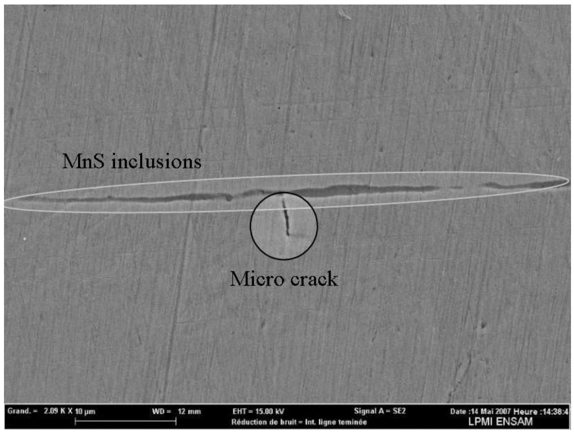

Figure 6: Several cracks are initiated near MnS inclusion interface

A realistic adaptated meshing can be performed by considering different options of generation. For instance, security distance can be given between each inclusions or orientation and position can be controlled directly. The goal is to create geometric entities in order to perform an adaptative mesh refinement near the interface in order to improve the calculus of gradients with any initial form of the R.E.V. (figure 7).

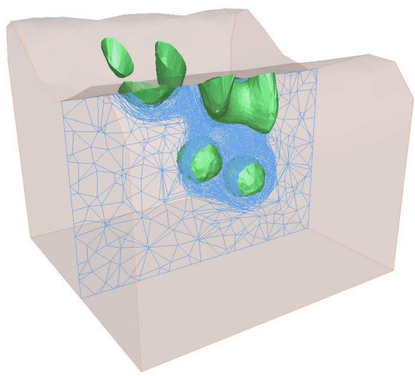

Figure 7: Geometry of a surface with a cluster of inclusions

Both inclusions and grains (defined by Voronoï tessellation) can be generated by considering an adaptated metric given to the MTC mesher developed by T. Coupez [2]. Finally, the R.E.V. is coated by a surrounding domain (figure 8). This domain is meshed and its role is to transmit boundary conditions to the R.E.V. and avoid edge effects for the microstructure computation. This structure can be tested numerically for a fatigue loading simulation in order to calculate the endurance function. However, the most difficult part is to determine the rheology of different entities to fit the microstructure behavior compared to the macroscopic behavior.

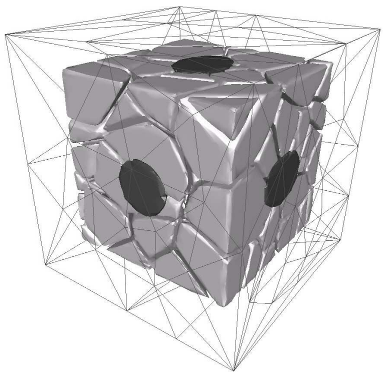

Figure 8: Mesh of a microstructure composed of 100 grains and 6 inclusions

In our study, only MnSs are studied and their behavior is approximately known [3]. Only the behavior of the matrix within inclusions are embedded must be determined (figure 9). Its rheological law is directly fitted with experimental data (for instance, data stemming from tension tests).

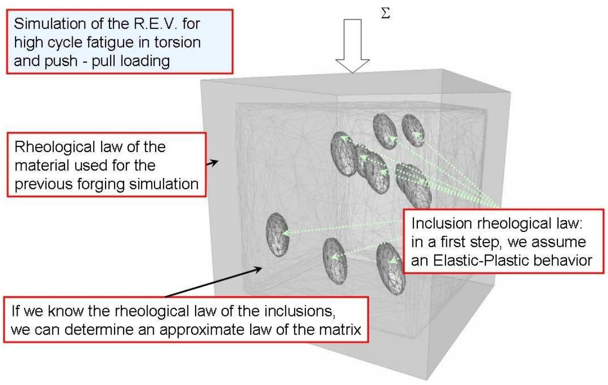

Figure 9: Simulation of a microstructure R.E.V.

By considering anisotropy is directly related to the orientation of inclusions, fiber vector can be associated to the direction of the first axle (the higher) of the inclusions. So, high cycle fatigue simulations are performed by changing the orientation of inclusions compared to the direction of the stress. Simple traction-compression or torsion tests are then simulated and the influence of the shape, the number and the orientation of the inclusions can be studied. Output parameters of such simulation give the endurance limits for the chosen direction which is directly associated to the macroscopic simulation by the means of fiber vector. Thus, we can predict the resistance of the forging component by knowing the endurance limits needed.

5 CONCLUSIONS

This work presents a new approach of fatigue analysis by considering directly the anisotropy in the Papadopoulos criterion. A representative microstructure is coupled with a standard fatigue simulation. This link between forming simulation and fatigue analysis at the microstructure scale is promising to improve fatigue computation predictions.

ACKNOWLEDGEMENT

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